

Age–Rotation–Activity Relations for M Dwarf Stars Based on ASAS Photometric Data

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ABSTRACT

Based on analysis of photometric observations of nearby M type stars obtained with ASAS, 31 periodic variables were detected. The determined periods are assumed to be related to rotation periods of the investigated stars. Among them 10 new variables with periods longer than 10 days were found, which brings the total number of slowly rotating M stars with known rotation periods to 12 objects.

X-ray activity and rotation evolution of M stars follows the trends observed in G–K type stars. Rapidly rotating stars are very active and activity decreases with increasing rotation period but the period-activity relation is mass-dependent which suggests that the rotation period alone is not a proper measure of activity. The investigated stars were grouped according to their mass and the empirical turnover time was determined for each group. It increases with decreasing mass more steeply than for K type stars for which a flat dependence had been found. The resulting Rossby number-activity relation shows an exponential decrease of activity with increasing Rossby number.

The analysis of space motions of 27 single stars showed that all rapidly rotating and a few slowly rotating stars belong to young disk (YD) whereas all old disk (OD) stars are slowly rotating. The median rotation period of YD stars is about 2 days and that of OD stars is equal to 47 days, *i.e.*, nearly 25 times longer. The average X-ray flux of OD stars is about 1.7 dex lower than YD stars in a good agreement with the derived Rossby number-activity formula supplemented with rotation-age relation and in a fair agreement with recent observations but in a disagreement with the Skumanich formula supplemented with the activity-rotation relation.

Stars: activity – Stars: rotation – Stars: low-mass, brown dwarfs

1 Introduction

Chromospheric-coronal activity is inherent to lower main sequence (MS) stars. In rotating stars with subphotospheric convection zones magnetohydrodynamic dynamo operates generating magnetic fields inside the zone and/or at the interface between the convection layer and the radiative core. After emerging above the photosphere, the magnetic field drives the heating of a stellar atmosphere and produces various activity phenomena like spots, plagues, flares and magnetized winds. Empirical data indicate that the activity level increases with increasing rotation rate (Hartmann and Noyes 1987, Maggio *et al.* 1987, Stępień 1989, 1994, Hempelmann *et al.* 1995). The observed period-activity relation for MS stars from a narrow spectral type shows a small scatter but when stars of all spectral types are plotted together, the scatter increases substantially (Noyes *et al.* 1984, Stępień 1994, Pizzolato *et al.* 2003). This clearly shows that period-activity relation varies with stellar mass. To decrease the scatter, rotation periods of stars of a given spectral type must be scaled down by a mass dependent quantity called the convective turnover time τ_c . Such a scaling is suggested by a simple parametric dynamo theory (Durney and Latour 1978, Gray 1982) in which the Rossby number $Ro = P_{\text{rot}}/\tau_c$ rather than rotation period is a primary parameter controlling the efficiency of field generation.

Values of turnover times for stars of various masses can be determined from theoretical models (*e.g.*, Gilman 1980, Gilliland 1985, Rucinski and VandenBerg 1986,

Kim and Demarque 1996) or empirically (Noyes *et al.* 1984, Stępień 1994, 2003, Pizzolato *et al.* 2003). The values of τ_c for G–K type stars, given by various authors, do not differ much but for M type stars they diverge badly. Theoretical models indicate a steep increase of τ_c with decreasing mass. For example, the theoretical value of turnover time for a $0.5 M_\odot$ star is 3–3.5 times longer than for a $1 M_\odot$ star (Kim and Demarque 1996, Rucinski and VandenBerg 1986 – in the latter case a slight extrapolation is needed because their models reach only $0.7 M_\odot$). Purely empirical determinations indicate that τ_c increases with decreasing mass down to about $0.8 M_\odot$, but then it levels off till about $0.6 M_\odot$ (Stępień 1994, 2003, Pizzolato *et al.* 2003). Due to a shortage of known periods for less massive, slowly rotating stars, the behavior of the empirical turnover time with decreasing mass beyond $0.6 M_\odot$ is very uncertain. There are indications that it may start increasing again but the situation has been obscure. The results of a recent analysis of angular momentum evolution of very low mass stars (VLMS), based on observations of young clusters, suggest that very long turnover times, predicted by theoretical models, do not agree with the observed rotation velocities of such stars. Sills, Pinsonneault and Terndrup (2000) noted that the relation $\omega_{\text{crit}}(\tau_c)$, where ω_{crit} is a critical angular velocity for the occurrence of saturation, breaks down if values of τ_c for low mass stars are extrapolated from the higher mass models of Kim and Demarque (1996). Lower values are in a better agreement with observations.

M type stars seem to share all characteristic properties of G–K type active stars: the most active stars have L_X/L_{bol} at the level of 10^{-3} *i.e.*, close to the upper limit for all active stars whereas the lowest measured X-ray fluxes are some 3 orders of magnitude lower as can be seen in the NEXXUS database (Schmitt and Liefke 2004). High activity level is related to stellar youth and it decreases with age so that old stars show notably decreased level of activity, both chromospheric (Delfosse *et al.* 1998, Silvestri, Hawley and Oswalt 2005) and coronal (Fleming, Schmitt and Giampapa 1995, Feigelson *et al.* 2004). The most active M stars rotate rapidly, with periods from a fraction of a day up to several days. Quite a number of rotation periods of such stars is known (Pizzolato *et al.* 2003 and references therein). Low activity stars seem to rotate slowly – they show values of $v \sin i$ below the present resolution threshold of about 2–3 km/s (Delfosse *et al.* 1998), which corresponds to a lower limit of several days for the rotation period. This is not a very restrictive condition because the lowest mass stars with such rotation periods are still in a saturation regime (Pizzolato *et al.* 2003). To extend the period-activity relation to the least active M type stars we need direct measurements of rotation periods of slowly rotating stars with periods several times longer than the saturation limit.

A standard method of measuring rotational periods is based on observations of stellar surface inhomogeneities which produce signal modulations over the rotational period. Several periods of chromospherically active stars have been determined in this way from rotational variations of CaII emission, carried out within the Mount Wilson program (Noyes *et al.* 1984, Donahue, Saar and Baliunas 1996 and references therein). The technique works well for F–K type stars. In M type stars the emission in CaII lines becomes a poor measure of the chromospheric energy losses and is difficult to measure. So far, the only M type star for which a rotation period has been determined from calcium emission modulation, is GJ 411 (=HD 95735) with spectral type M2V (Noyes *et al.* 1984). Star-spots produce another type of surface inhomogeneities, observable with a broadband photometry. A rotational modulation of stellar brightness has been observed in many active stars, including those of M type (see Messina *et al.* 2003 for a recent review). High activity stars have typical amplitudes of several percent which is easy to detect, particularly for short rotation periods. Low activity stars are expected to have much less spottedness producing correspondingly weaker light variations and on a much longer time scale (Messina *et al.* 2003). In addition, possible variations of

a spot pattern on a time scale comparable to the rotation period can mask rotational modulation. Long time series of observations are needed to filter out the correct value of a period. Because of all these problems, only very few detections of rotation periods of slowly rotating stars have been reported from the observations of star-spots.

In the last decade many very low mass stars (VLMS) and brown dwarfs have been detected using high sensitivity observational techniques in red and infrared. Several studies followed, including searches for rotation periods and measurements of $v \sin i$. Most of the studies are concentrated on young clusters (Scholz and Eislöffel 2005 and references therein) but several field objects have also been observed. The results show that many observed VLMS are active and fast rotating. The transition from partly to fully convective stars has no apparent influence on their activity and/or rotation (Delfosse *et al.* 1998, Mokler and Stelzer 2002). The average value of $v \sin i$ apparently increases with the advancing spectral type from early M to late M and L (Delfosse *et al.* 1998, Mohanty and Basri 2003, Scholz and Eislöffel 2005). This is usually interpreted in terms of increasing time scale for spin down with decreasing mass but a detailed age–activity–rotation relation for M type stars of various masses is unknown. One should not forget, however, when interpreting observations of stars with ages of about 1 Gyr or less, that evolutionary effects should also be taken into account due to a rapid increase of the approach time to ZAMS of VLMS, up to 3 Gyr for least massive stars (Baraffe *et al.* 1998). More stars with known age, activity level and rotation period (particularly those inactive and/or slowly rotating) will help in solving the problem of spin down and activity decrease of low mass stars.

The present investigation is aimed at enlargement of the number of M type stars with known rotation periods. A particular care is taken to detect slowly rotating stars. To this purpose an extensive data set of photometric observations obtained during the automated sky survey ASAS (Pojmański 1997, 2004) is used. To assure a minimum reasonable accuracy, we analyzed M stars brighter than a visual magnitude $V = 12.5$ mag which restricted our sample to M0–M3.5 type stars only, with an exception of Proxima (M5.5).

Section 2 describes the star selection criteria and method of analysis. In Section 3 the results of the period search are presented and interpreted in terms of empirical turnover time and age–activity–rotation relations. Section 4 contains the summary of the main conclusions.

2 Star Selection and Analysis

ASAS cameras are located at Las Campanas Observatory, Chile, and the observations cover the sky south of declination $+28^\circ$. At the angular resolution of $14''/\text{pixel}$ several visual binaries are not separated.

The most accurate ASAS photometric measurements are obtained for stars with V magnitudes between 8.0 and 12.5. Brighter stars are usually saturated, whereas the observational errors increase rapidly for fainter stars. For the period search we selected stars with the following properties:

- (i) X-ray flux is known from Hünsch *et al.* (1999) or from NEXXUS database
- (ii) spectral type is M,
- (iii) $8 < \bar{V} < 12.5$, where \bar{V} is a mean V magnitude.

180 stars from the ASAS database fulfilled these conditions. Only good quality photometric data (with quality grade “A” and “B” – Pojmański 2006, private communication) were included into the period analysis.

Objects monitored by ASAS are typically observed once per night or, sometimes, even more sparsely, depending on weather. The Nyquist frequency corresponds in this

case to the period of 2 days. We looked for periods from 0.2 d up to the length of an observational run in a single season (≈ 100 days). We assumed that season to season variations are not connected with rotation and we eliminated them before performing period search. Because the shortest periods, found in the search, are shorter than the Nyquist limit, it is probable that some of them may be aliases of the true periods.

Many late type stars flare from time to time with typical duration of a flare of less than one day. Such events should be eliminated before period search, because points with large deviations from the mean value have large weights in period searching algorithms. Unfortunately, the ASAS observations are not well suited for identification of stellar flares because they usually manifest themselves as single data points indicating a substantial brightening. To get rid of them we rejected data points deviating from the mean seasonal magnitude by more than 3.5 standard deviations, or from the grand mean value by more than 0.35 mag.

Apart from sudden brightenings many similar light drops occur within the data. It is not clear what causes them. The simplest explanation relates them to wrong measurements. Magnitude measurements fainter than the mean value are more frequent than those above the mean (Pojmański 2006, private communication). We applied the same procedure to them as in case of brightenings. Altogether, we rejected 229 drops and 87 brightenings, which is about 0.6% of all data points. Only one star, GJ 551 (= Proxima) happened to brighten over two consecutive observations: first by 1.13 mag above the mean level and 1.5 hour later it was still brighter by 0.35 mag. In other cases we do not have neighboring observations indicating significant brightness deviations from a normal level. There were on average 285 measurements per star left, extended over 6 seasons.

Late type active stars often show season-to-season light variations with amplitudes of the order of 0.1 mag. A good example of such star is AB Dor which was observed nearly continuously over more than 20 seasons (Kürster *et al.* 1997, Järvinen *et al.* 2005). The long term variations are usually interpreted as resulting from activity cycles. Several stars from our sample also show seasonal variations. Because of that we have done period search separately for each season unless the number of useful observations in the particular season was lower than 50 data points. Data from such seasons were merged with the ones from neighboring seasons and analyzed together. A similar period search was also performed on the whole data set after eliminating season to season variations. We used the AOV algorithm, together with the subroutine CAOv which can be downloaded from the Alex Schwarzenberg-Czerny homepage <http://www.camk.edu.pl/~alex/>. A detailed description of the program can be found in Schwarzenberg-Czerny (1989). In short, we are folding and binning data points with a trial period, and for a given number of bins and data points we obtain AOV statistics

$$\Theta_{\text{AOV}} = s_1^2 / s_2^2 \quad (1)$$

where

$$(r-1)s_1^2 = \sum_{i=1}^r n_i (\bar{x}_i - \bar{x})^2 \quad (2)$$

and

$$(n-r)s_2^2 = \sum_{i=1}^r \sum_{j=1}^{n_i} (x_{ij} - \bar{x}_i)^2 \quad (3)$$

with r being a number of bins, n_i – number of data points in the “ i -th” bin, \bar{x}_i – mean value of data points in the “ i -th” bin and \bar{x} – mean value of all data points. We used six phase bins and assumed that the detected periodicity is significant when $\Theta_{\text{AOV}}(P) \geq 8.0$, unless the indicated period was very close to 1 day due to a slow, systematic drift of the

stellar brightness over the whole season. Such periods were treated as spurious. The results of the period search are presented and discussed in Section 3.

3 Results and Discussion

3.1 Period Search

Out of 180 analyzed stars only 31 showed statistically significant periodic variations. Table 1 lists basic data for them and the results of the period search. Spectral types, absolute magnitudes and X-ray data are taken from NEXXUS. For X-ray variable stars average values of $\log R_x$ are taken. Bolometric corrections were calculated from color indices $R - I$, using a formula from Delfosse *et al.* (1998): $BC = -0.083 - 0.501(R - I) - 0.646(R - I)$.

Table 1
Basic data for stars with significant periodic variability

name	ASAS des.	d pc	M_V mag	Sp	($\log L_b$)	($\log R_x$)	P days	Θ_{AoV}	amp mmag	mass M_\odot
GJ 84	020504-1736.9	9.4	10.32	M2.5	32.08	-4.4	44.51	24.4	26	0.45
GJ 103	023422-4347.8	11.5	8.55	M0	32.53	-2.8	1.563	64.7	63	0.65
GJ 1054A	030755-2813.2	18.0	8.96	M0	32.36	-3.0	0.513	15.4	18	0.63
HIP 17695*	034723-0158.3	16.3	10.53	M3	31.98	-3.0	3.880	25.1	39	0.43
Gl 176	044256+1857.5	9.4	10.11	M2	32.10	-4.7	38.92	19.5	34	0.48
GJ 2036A	045331-5551.6	11.2	10.89	M2	31.95	-3.0	0.849	9.4	11	0.38
GJ 182	045934+0147.0	26.7	7.96	M0.5	32.75	-3.1	4.410	19.9	27	0.69
GJ 3331A	050650-2135.1	11.8	9.93	M1.5	32.10	-3.0	0.341	8.4	9	0.50
GJ 205	053127-0340.6	5.7	9.18	M1.5	32.37	-4.7	33.61	10.3	8	0.60
GJ 3367	054717-0000.8	24.4	9.05	M0	32.31	-3.4	12.05	8.9	14	0.62
GJ 358	093946-4104.1	9.5	10.86	M2	31.94	-3.9	25.26	21.3	14	0.39
GJ 375	095834-4625.5	15.9	10.26	M3.5	32.30	-3.1	1.877	11.0	22	0.37
GJ 382	101217-0344.7	7.8	9.81	M1.5	32.18	-4.7	21.56	21.6	11	0.52
GJ 431	113146-4102.8	10.5	11.42	M3.5	31.81	-3.5	14.31	10.5	31	0.33
TWA 5A	113156-3436.5	50	7.88	M1.5	33.04	-3.1	0.7767	21.2	36	0.70
GJ 494	130046+1222.5	11.4	9.46	M0.5	32.25	-3.4	2.889	15.4	16	0.56
GJ 551	142942-6240.8	1.3	15.49	M5.5	30.76	-3.8	82.53	24.0	21	0.11
GJ 569A	145429+1606.1	9.8	10.24	M3	32.05	-3.7	13.68	8.3	10	0.46
GJ 9520	152152+2058.7	11.4	9.83	M1.5	32.19	-3.3	0.369	8.4	13	0.51
GJ 618A	162003-3731.7	8.5	10.96	M3	31.89	-4.7	56.52	9.5	11	0.38
GJ 2123A*	165648-3905.7	14.6	10.36	M3	32.03	-2.5	0.320	65.9	46	0.45
GJ 669A	171954+2630.1	10.7	11.28	M3.5	31.87	-3.2	0.950	10.3	30	0.35
GJ 674	172839-4653.7	4.5	11.10	M3	31.80	-4.2	33.29	9.5	8	0.37
GJ 729	184949-2350.2	3.0	13.09	M3.5	31.21	-3.5	2.869	15.3	10	0.20
GJ 799A/B	204151-3226.1	10.2	10.94	M4.5	32.17	-3.0	0.7813	16.8	13	0.38
GJ 803	204509-3120.5	9.9	8.82	M1	32.52	-2.9	4.848	30.5	46	0.64
GJ 1264A	214905-7206.1	16.1	8.76	M0.5	32.53	-3.3	6.669	68.5	21	0.64
Gl 841A	215741-5100.4	16.2	9.31	M2.5	32.50	-3.2	1.124	12.4	10	0.58
GJ 867A	223845-2037.3	8.6	9.42	M1.5	32.36	-3.2	4.233	11.1	10	0.57
GJ 890	230819-1524.6	21.8	9.18	M0	32.24	-3.0	0.431	11.0	37	0.60
GJ 897A	233247-1645.4	15.4	10.01	M2	32.22	-3.1	4.828	12.0	14	0.49
GJ 411	110321+3558.2	2.54	10.46	M2	31.89	-4.9	48.0	-	-	0.44
GJ 699	175749+0441.6	1.8	13.25	M4	31.17	-5.4	130.	-	-	0.20

Consecutive columns give names, ASAS designations (= coordinates given in the order: RA-Dec.), distances, absolute visual magnitudes, spectral types, bolometric luminosities, $\log R_x = \log(L_x/L_{bol})$, detected rotation periods, values of the parameter Θ_{AoV} at the listed period, amplitudes of light variations, and estimated stellar masses.

For two stars with no $R - I$ indices marked with asterisk the bolometric corrections were calculated from the absolute visual magnitudes, as suggested by Pettersen (1983): $BC = -0.397M_V + 2.386$.

Stellar masses were calculated from the absolute magnitude M_V using the formula derived by Delfosse *et al.* (2000): $\log(M/M_\odot) = 10^{-3}(0.3 + 1.87M_V + 7.614M_V^2 -$

$$1.698M_V^3 + 0.060958M_V^4).$$

In case of tight binaries, the magnitudes given in Table 1 were not corrected for fainter components, so their masses may be overestimated. The exception is GJ 375 which consists of nearly identical components (Montes *et al.* 2006). The formula given by Delfosse *et al.* (2000) applies only to stars with $M_V > 9$ mag. For a few brighter stars the masses were found using the calibration given by Andersen (1991). The last two entries in Table 1 are taken from literature.

Left panels of Figs. 1–4 present all photometric measurements of periodic stars vs. $\text{hjd} = \text{HJD} - 2450000$ d with observations showing periodic variations marked as filled symbols. Right panels show filled symbols folded with the detected periods after applying corrections for seasonal variations. In most cases periodic variability is seen over the whole observational interval without any significant phase shift from one season to another, but a few stars show transient periodic variability. The number of filled symbols and the total number of analyzed observations are given for each star.

Periods longer than 10 days were found only for 11 stars, *i.e.*, about 30%, of all detected periodic variables. We believe that such a low proportion of slowly rotating stars is a result of observational selection: the expected amplitudes of periodic variations of high activity stars are substantially higher, hence easier to detect than in case of inactive stars. Several more M type stars with short rotation periods of the order of one or a few days are known in the literature (Messina *et al.* 2003) but we found only two stars with long rotation periods: GJ 411 with $P_{\text{rot}} = 48$ d (Noyes *et al.* 1984), and GJ 699 (Barnard star) with $P_{\text{rot}} \approx 130$ d (Benedict *et al.* 1998). We include both stars into the further analysis.

Notes on individual stars.

GJ 84 is a visual binary with the secondary component lying $0''.44$ from the primary (Golimowski *et al.* 2004). The luminosity difference is 4.6 mag in the F110W filter at the NICMOS camera, so the contribution of the secondary is negligible, both in the V-band and (most likely) in X-rays. Aliases 0.9749 d and 1.020 d are rather excluded due to the low X-ray activity of the star.

GJ 103 (CC Eri) is a spectroscopic binary with components of spectral types K7 + M3 and the combined type M0 (NEXXUS). The photometric period is the same as the orbital period (Evans 1959).

GJ 1054A is a component of double line binary with an unknown period (Gizis, Reid and Hawley 2002) which, however, according to the authors, should be short. The most significant period in the ASAS photometry is given in Table 1 (0.513 d, $\Theta_{\text{AoV}} = 15.4$), its alias 18.86 d is also significant, ($\Theta_{\text{AoV}} = 13.3$) but we consider it as less likely due to very high activity of the star.

GJ 182 is a single flare star with a rotation period known from literature of 4.565 d (Byrne *et al.* 1984). We have not found any significant variability at this period. Maximum value of $\Theta_{\text{AoV}} = 26.4$ is at a period of 1.2921 d for the 106 data points between hjd 2496.9 and 3110.5, however we consider the period of 4.410 d with $\Theta_{\text{AoV}} = 19.9$, obtained for the whole data set, as the most probable.

GJ 2036A was observed together with GJ 2036B by ASAS. Component B is at angular distance $8''$ and is fainter by about 1 mag in the V-band. The total V magnitude of the binary as measured by ASAS is 10.75 mag. We attribute the photometric variability to the brighter component.

GJ 3331A is the brightest component of the triple system. The pair BC is $8''.2$ from the primary and the differences in magnitudes between components A and BC are $\Delta V = 0.722$, $\Delta R = 0.574$, $\Delta I = 0.220$ (Jao *et al.* 2003). We assume that photometric variability is related to GJ 3331A. Its parallax measurement has a large error (NEXXUS database) so we do not include this star in Table 3.

GJ 205 – aliases at 0.971 d and 1.028 d are rather excluded due to low activity of

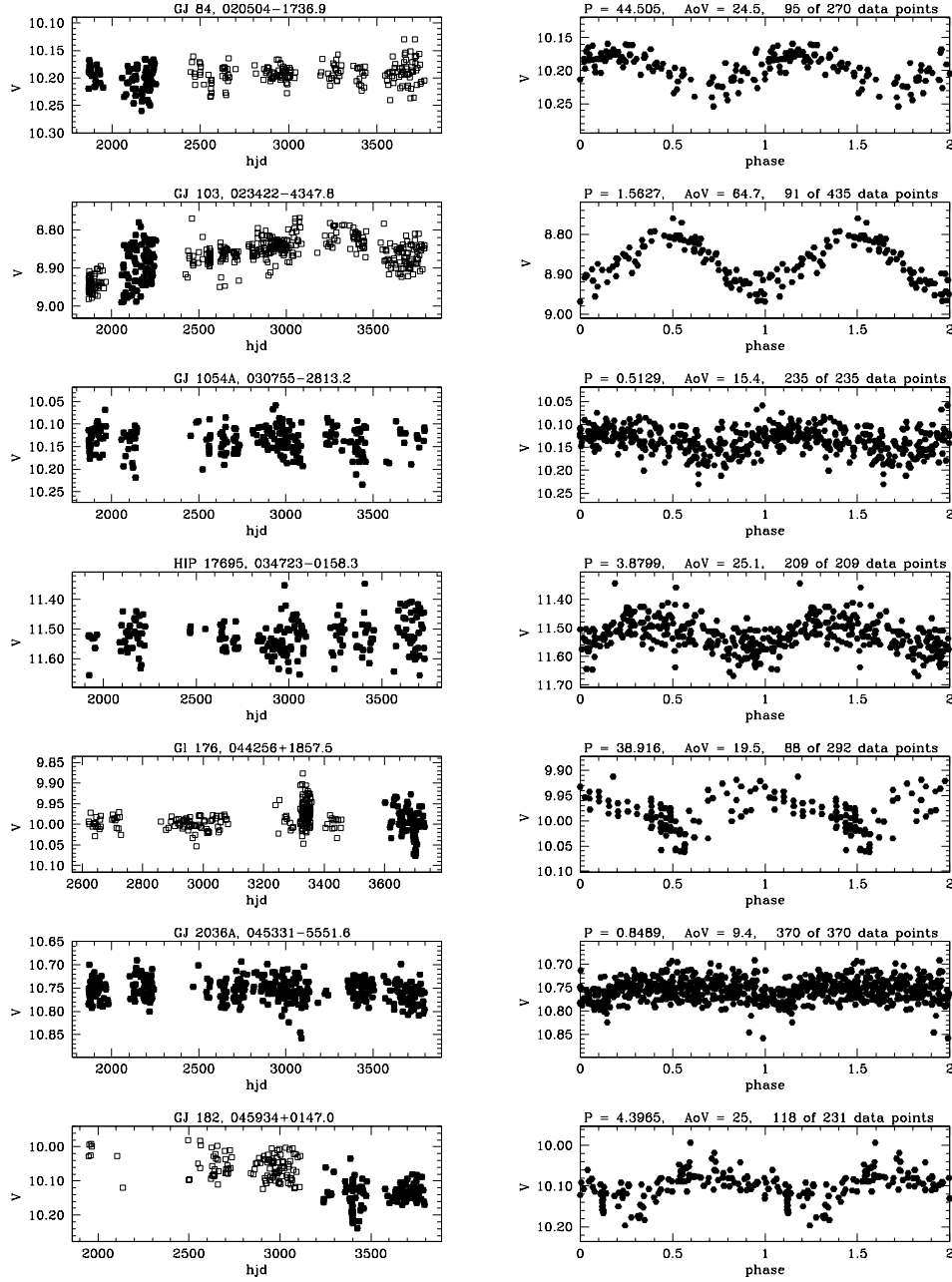


Fig. 1. Photometric measurements of periodic stars vs. hjd = HJD -2 450 000 d (*left panels*). Observations showing periodic variations are plotted as filled symbols. *Right panels* show filled symbols folded with the listed period. The brightness at right panels is corrected for seasonal variations of luminosity. The number of filled symbols and the total number of analyzed observations are also given.

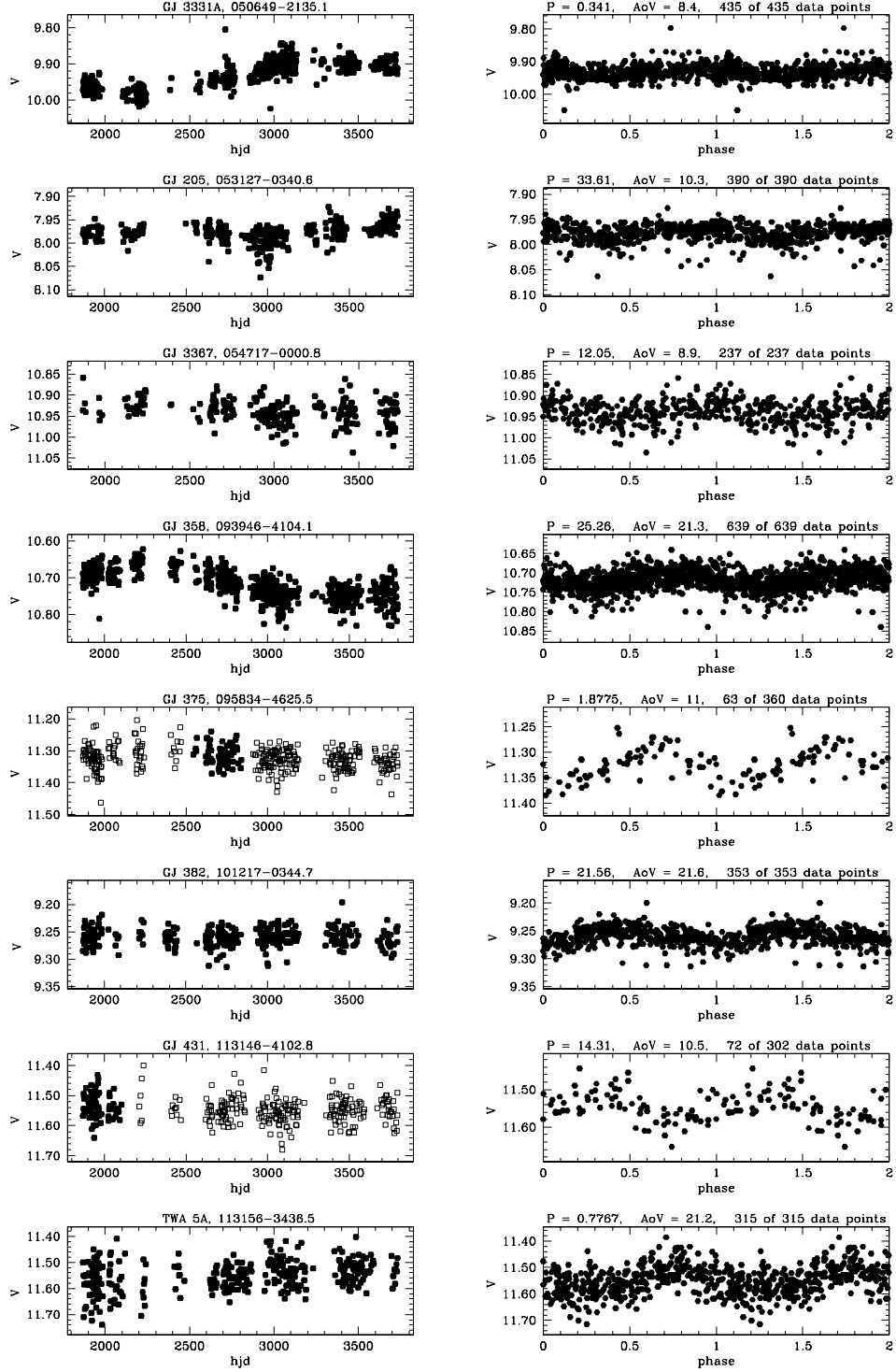


Fig. 2. Same as Fig. 1

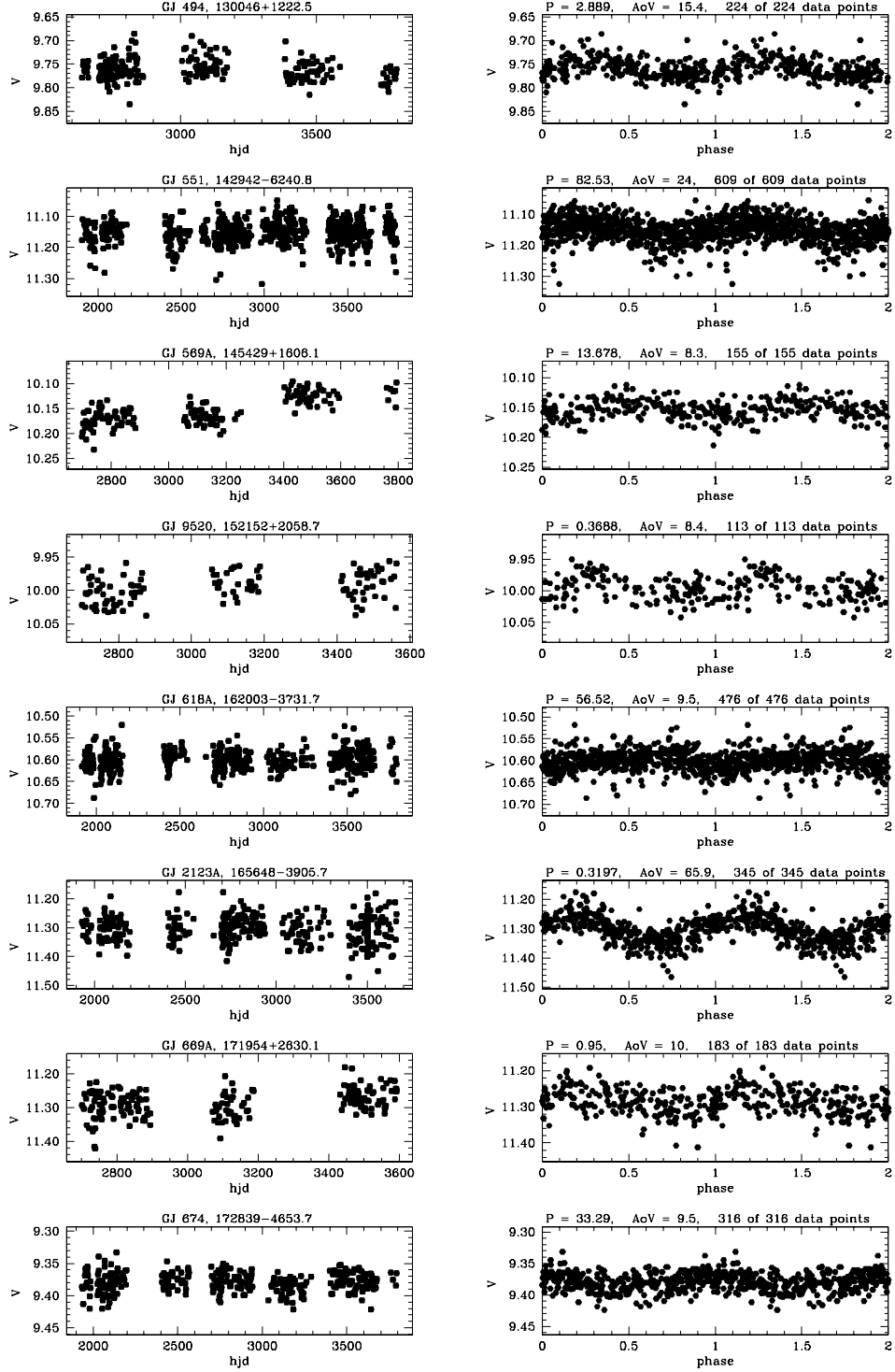


Fig. 3. Same as Fig. 1

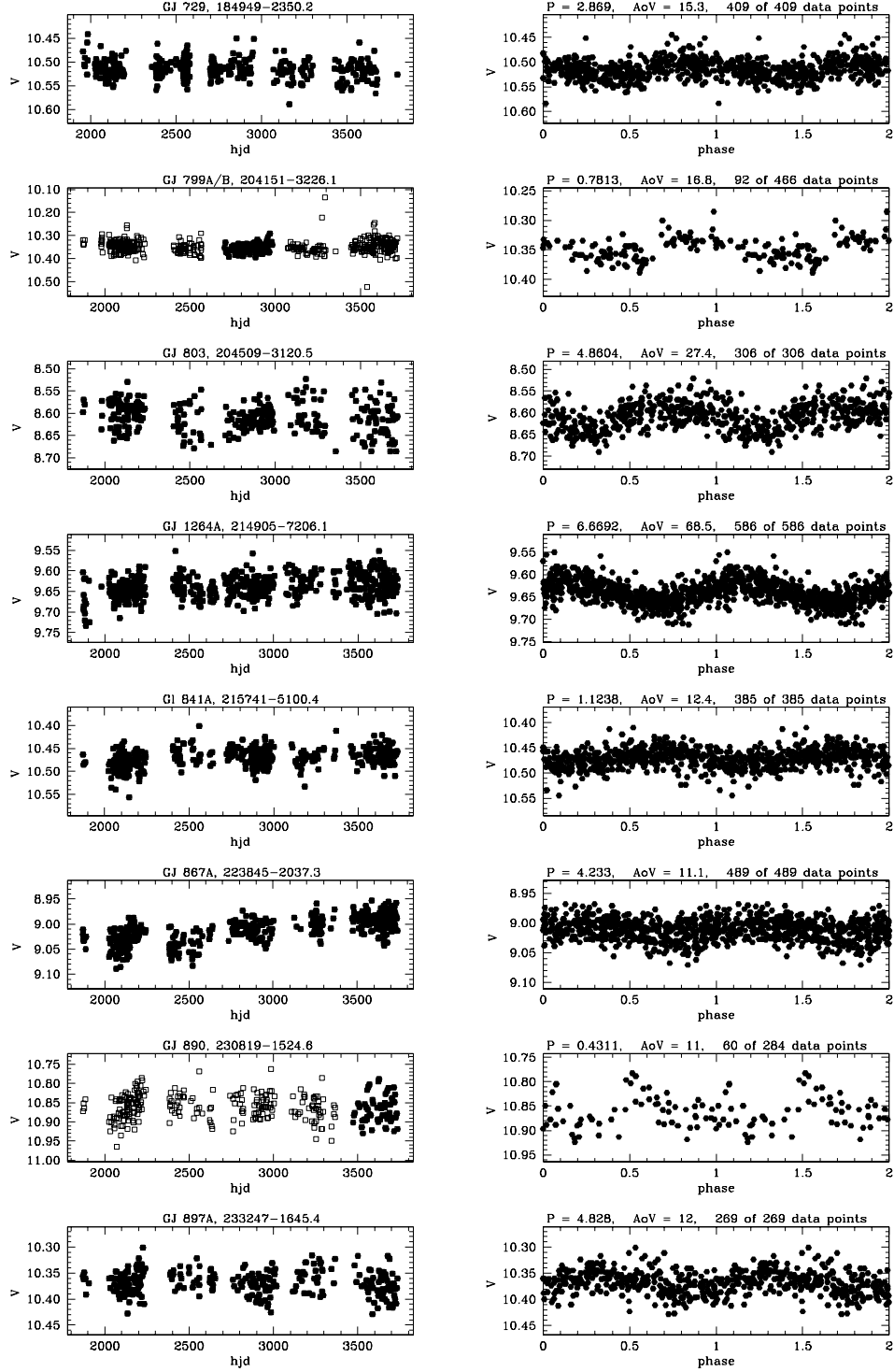


Fig. 4. Same as Fig. 1

the star.

GJ 375 is a double line spectroscopic binary with a period of 1.875 d and nearly identical components (Montes *et al.* 2006). Photometric period is identical with the spectroscopic one. Mass, given in Table 1, refers to one component.

TWA 5 – appears to be a multiple system. This is a young system belonging to the TW Hya association. The main component consists of a spectroscopic binary and the third component is separated by $0''.054$ (Brandeker *et al.* 2003). All three stars are of spectral type M1.5. In addition, there is also a brown dwarf at angular distance of $2''$. Based on XMM observations Argiroffi *et al.* (2005) give $\log(L_X) = 29.8$ and $\log(L_X/L_{\text{bol}}) = -3.1$ for the triple M dwarf system. The photometric period found in the ASAS data may probably be related to the orbital period of a spectroscopic binary. Another possible period is an alias 3.512 d. The mass given in Table 1 is based on the absolute magnitude of the total system and, therefore, very likely overestimated.

GJ 494 (DT Vir) has a low luminosity companion at angular separation of $0''.48$ (February 2000, Beuzit *et al.* 2004), fainter in the *K* band by 4.4 mag, which makes its contribution completely negligible, both in *V* and in X-rays.

GJ 551 = Proxima has the lowest luminosity in our sample of stars with detected periods. ASAS photometric data indicate a clear periodicity of 82.5 days, very close to the rotation period found by Benedict *et al.* (1998). We have not found any significant signal at a period of 42 days, visible in part of the data analyzed by Benedict *et al.* (1998), or around 30 days, reported by Guinan and Morgan (1996).

GJ 618A has a nearby companion ($5''.4$) of spectral type M5, which is fainter in the *V*-band by 3.5 mag. This makes its photometric contribution completely negligible and we can safely assume that the photometric variability is related to the brighter component. Nevertheless, the X-ray luminosity of M5 type star may contribute significantly to the total X-ray emission of the binary if the star is very active, so the value of $R_x = 4.7$, listed in Table 1, should be treated as an upper limit for the X-ray flux of GJ 618A.

GJ 2123A is a very active M3 star with an M4 companion about 1.8 mag fainter in the *V*-band, lying at angular distance of $2''.8$. We attribute the photometric variability to the brighter component.

GJ 669A has a companion at angular distance of $16''$, fainter by about 1.6 mag in the *V*-band. Both stars are unresolved in the ROSAT and ASAS data.

GJ 674, there are also significant peaks of AoV statistics at aliased periods of 0.9709 d and 1.028 d with $\Theta_{\text{AoV}} \approx 10$. We prefer 33.29 d due to low activity of the star.

GJ 799 (AT Mic) is a visual binary with angular separation between components of $3''.3$, too close to be resolved either by ROSAT or by ASAS. Both components have almost the same luminosity in *V*-band and we assume that their X-ray luminosity is also the same. Values listed in Table 1 are related to a single component.

GJ 803 (AU Mic) is a young, single star with rotation period of 4.865 d (Torres *et al.* 1972). We see the strongest signal at a period of 4.8482 d in the ASAS data (62 data points between hjd 3450.9 and 3718.5), but there is also a significant power at 4.8604 and 4.8617 d for the whole data set. This may be related to the differential rotation of the star.

GJ 1264A has a companion at a distance of $1''.3$, fainter by 1.2 mag in the *V*-band. The stars are unresolved in ROSAT and ASAS data. We assume that all activity and variability is related to the brighter component.

GJ 841A is a spectroscopic binary with a period of 1.1248 d (Jeffries and Bromage 1993). A similar period of 1.1237 d is visible in the whole ASAS data set (with the AoV statistics equal to 12.4). More significant (aliased) period of 0.5283 d with $\Theta_{\text{AoV}} = 12.5$ does not fit to the Jeffries and Bromage data.

GJ 867A (FK Aqr) has a companion separated by $23''.5$ and fainter by 1.9 mag in the V -band. The stars are unresolved in ROSAT and ASAS data. GJ 867A is a spectroscopic binary with an orbital period of 4.083 d (Herbig and Moorhead 1965). Bopp and Espenak (1977) also found a photometric period of 4.08 d, but Byrne *et al.* (1987) claim a photometric period of 4.39 d. Cited above photometric periods are close to, but not identical with our value 4.232 d. The mass given in Table 1 is likely overestimated.

GJ 890 (HK Aqr). Barnes and Collier Cameron (2001) give a rotation period of 0.4307 d for this star. We obtained a similar period of 0.4311 d.

GJ 897A has a companion separated by $0''.5$ and fainter by 0.5 mag in the V -band. The stars are not resolved by ROSAT and ASAS. We attribute the photometric variability to the brighter component.

3.2 Empirical Turnover Times

To derive the empirical turnover times for low mass stars the procedure applied by Stępień (1994, 2003) was used, except that the analyzed stars were grouped in the present paper according to mass rather than $B - V$. Natural breaks in the mass distribution were used for this grouping. Two stars: GJ 182 and TWA 5A stand out as the most massive stars. Because no slowly rotating stars with similar masses occur in Table 1, the stars were excluded from the further analysis. 10 “high mass” stars have masses between $0.56 M_{\odot}$ and $0.65 M_{\odot}$, 10 “medium mass” stars have masses between $0.43 M_{\odot}$ and $0.52 M_{\odot}$ and 8 “low mass” stars have masses between $0.33 M_{\odot}$ and $0.39 M_{\odot}$. Two stars with masses $0.2 M_{\odot}$ and one with $0.11 M_{\odot}$ are termed “very low mass” stars (Table 2).

Table 2

Values of the coefficients a and b from Eq. (4) for four mass intervals and the resulting turnover times

stars	av. mass	No. of stars	a	b	$\tau_c(\text{d})$
high mass	0.61	10	-2.94 ± 0.08	-0.050 ± 0.006	30 ± 4
medium mass	0.47	10	-3.02 ± 0.18	-0.040 ± 0.007	38 ± 6
low mass	0.37	8	-3.14 ± 0.08	-0.029 ± 0.003	53 ± 6
very low mass	0.17	3	-3.00	-0.016 ± 0.005	95 ± 30

Fig. 5 presents values of $\log R_x$ vs. P_{rot} for all four groups of stars. Different groups are marked with different symbols. Linear relations of the form

$$\log R_x = a + bP_{\text{rot}} \quad (4)$$

are fitted to the data within each group. For the first three groups both coefficients were determined with the least squares method. Because only one short period star with very low mass is plotted in Figs. 1–4 the value of a in this case was assumed to be equal to -3 . Table 2 gives values of the coefficients from Eq. (1) for each group, together with their errors. The value of the coefficient b for very low mass stars is extremely uncertain due to a low number of data.

Values of empirical turnover time can be found from relation: $\tau_c = -cb^{-1}$, where the normalization factor c remains undetermined unless one wants to compare the obtained values of τ_c to values obtained with another method (for details, see Stępień 1994). A value of the normalization coefficient $c = 1.515$ was found by fitting the presently

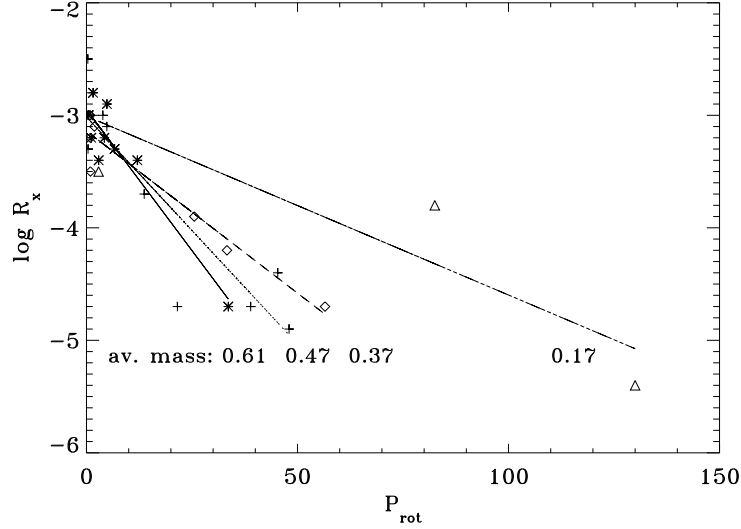


Fig. 5. X-ray to bolometric flux ratio vs. rotation period for stars from Table 1. Straight lines are the least square fits to observational data grouped according to mass. Asterisks correspond to high mass stars, pluses to medium mass, diamonds to low mass and triangles to very low mass stars. Average mass for each group is indicated at the fitted line.

calculated turnover times, supplemented with the values obtained by Stepień (1994) from the X-ray data of G–K type stars ($B - V$ between 0.55 mag and 1.25 mag), to the relation determined by Stepień (2003) from CaII emission. The latter relation was found by using correctly reduced values of the net calcium emission flux, contrary to, so called, excess calcium emission flux used earlier by Stepień (1994). The last column of Table 2 gives normalized values of τ_c and Fig. 6 shows τ_c vs. mass. The relation from Stepień (2003) is plotted as a solid line and the values of turnover times found from X-ray data are given with their errors. The older data are plotted with $B - V$ values transformed to stellar mass. It is seen from Fig. 6 that, after passing a plateau for masses in the range $0.8 M_\odot$ – $0.6 M_\odot$, turnover time increases again for still lower masses. The increase is not as steep as resulting from the extrapolation of the theoretical values (Kim and Demarque 1996). Overplotted are values of turnover times found by Pizzolato *et al.* (2003). They used a different sample of stars and a somewhat different method but the agreement between both sets of data is satisfactory. They were not able to determine turnover times for stars less massive than $0.6 M_\odot$ due to a shortage of data for slowly rotating stars.

Fig. 7 shows the X-ray data of the stars from Fig. 5 plotted vs. Rossby number which was calculated for each star using turnover time from Table 2. As expected, the scatter is considerably lower than in Fig. 5 and the exponential relation between R_x and Ro seems to describe satisfactorily the fit $\log(R_x) = -(3.05 \pm 0.07) - (1.45 \pm 0.12)Ro$. Similar relation has been shown to hold for G and K type stars (Stepień 1994: $\log(R_x) = -(3.71 \pm 0.27) - (1.46 \pm 0.13)Ro$). The free term differs somewhat between both relations but the slope agrees very well.

3.3 Age–Period and Period–Activity Relations

Active stars from the lower MS are expected to lose angular momentum *via* a magnetized wind. Observations of stellar clusters show indeed that single stars spin down with age. Unfortunately, accurate measurements of rotation periods are available for

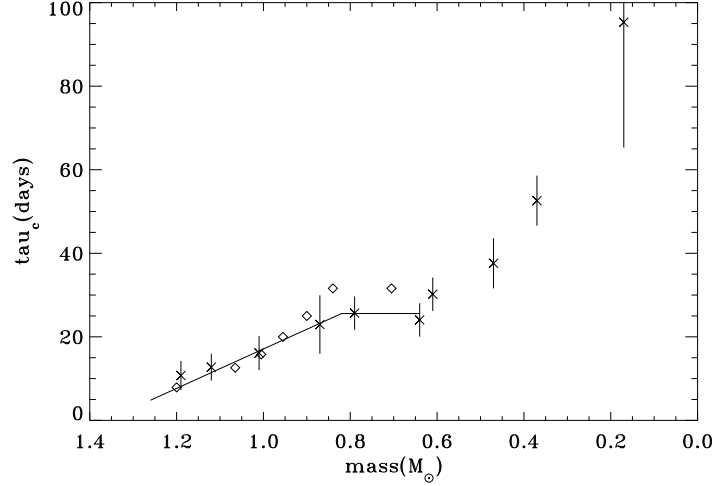


Fig. 6. Empirical turnover times with error bars, determined from X-ray fluxes, vs. stellar mass. Data from Table 2 are supplemented with older determinations for more massive stars (Stepień 1994). Values of the turnover times are scaled to data found from calcium emission fluxes (solid line, Stepień 2003). Diamond give values of empirical turnover times from Pizzolato *et al.* (2003).

members of young clusters only. In case of M 67, the oldest cluster (4 Gyr) for which useful measurements exist, no more than just $v \sin i$ values have been measured for some stars. The available data may be sufficient to calibrate the age–rotation relation for solar type stars but M type stars evolve substantially slower and we need accurate data for stars much older than members of the investigated clusters. Such stars are expected to exist among field stars in the solar vicinity but accurate determination of field star age is difficult. We are forced to use proxies only statistically related to age. A commonly used proxy of this kind is kinematic class (Eggen 1969) based on the (U, V) plane, where U , V and W are the components of space motion of a star. Table 3 gives star names, components of proper motions in right ascension and declination, radial velocity, the calculated values of the U , V and W components for stars from Table 1 for which complete data, including radial velocity, are available. Proper motions and radial velocities are from the NEXXUS database, U -axis is directed opposite to the Galactic center, V -axis – in direction of Galactic rotation, W -axis – in direction of the North Galactic Pole. YD means Young Disk with kinematical parameters $-20 < U < 50$, $-30 < V < 10$, $-25 < W < 10$, OD – Old Disk, YD/OD Young or Old Disk, OD/H – Old Disk or Halo.

Known spectroscopic binaries with short periods were excluded because their activity levels and variability periods (assuming synchronization of orbital and rotational period) are not related to ages. The last column gives kinematic class. We identify 20 stars belonging to young disk (YD), 1 star falling at the border between young and old disk (YD/OD) and 4 stars belonging to old disk (OD). Both stars added to our sample from literature belong to old disk (Fleming *et al.* 1995), so we have all in all 6 OD stars, although GJ 699 may even belong to halo (Delfosse *et al.* 1998).

As it is seen from Table 3, all short period stars belong to YD or YD/OD. However, there are also 4 YD stars in our sample with periods longer than 10 days, including Proxima with a period of 82.5 d – the longest one found in our search. Such a mixture of rapidly and slowly rotating stars is not surprising. YD stars are on average about 3–4 Gyr old (Meusinger, Stecklum and Reimann 1991) but individual stars may have ages up to several Gyr. If Proxima has a common origin with α Cen (Wertheimer and Laughlin 2006), its age is about 6 Gyr, yet its kinematical characteristics are typical of

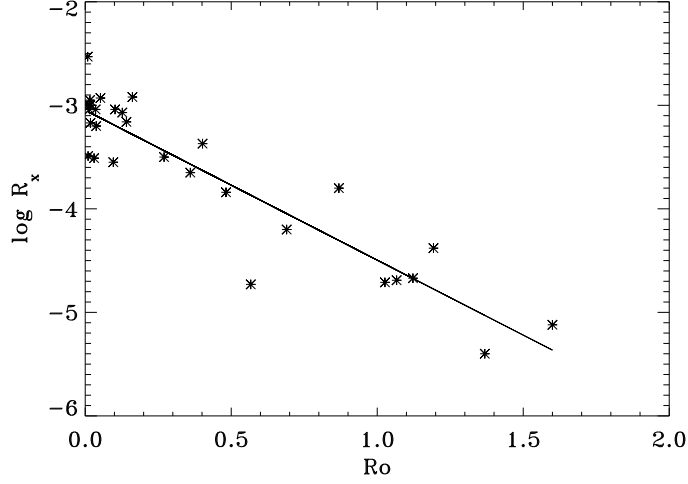


Fig. 7. X-ray to bolometric flux ratio vs. Rossby number $Ro = P_{\text{rot}}/\tau_c$ calculated at the base of empirical convective turnover times from the Table 2. The straight line gives the best fit (see text).

young disk.

The average period of YD stars is 9.4 d and the median value is about 2 d. Contrary to YD stars, we do not have any rapidly rotating stars among OD objects. All six stars have periods longer than 30 d with a mean value of 58.8 d and a median of 47 d. We assume that OD stars have age of the order of 10 Gyr (Meusinger *et al.* 1991).

Comparison of both median values indicates that angular momentum of M type stars decreases, on average, by a factor of 25 in 10 Gyr but this factor may vary between 5 and 100 if the initial rotation periods of individual stars are taken from observations of young clusters (Barnes 2003).

Based on observations of $v \sin i$ of solar type stars Skumanich (1972) found an empirical relation describing the dependence of the rotation period on time: $P_{\text{rot}} \propto t^{1/2}$. More numerous observations of stars in several young clusters showed that the Skumanich law breaks down for rapidly rotating stars which show the effect of saturation, visible as a flattening of $P_{\text{rot}}(t)$ when $t \rightarrow 0$. Considering slowly rotating stars we still may ask, how universal the Skumanich law is? Is it mass independent? A number of formulas describing spin down rate of single stars have been suggested in the literature. One of them, derived by Kawaler (1988), has a form: $d\omega/dt = A\omega^3$, where the coefficient A depends on stellar mass and radius. Neglecting time variability of stellar parameters we recover the Skumanich law: $\omega \propto At^{-1/2}$. Here, the dependence on stellar parameters appears only through the coefficient of proportionality A whereas the functional dependence on time ($t^{-1/2}$) is mass independent. Sills *et al.* (2000) assumed that the Kawaler formula can be applied even to VLMS. Another spin down formula, in which mass dependence occurs only *via* an exponential term containing turnover time, was derived by Stepień (1988, 2006)

$$-\frac{d\omega}{dt} = 7 \times 10^{-9} \omega e^{-Ro/0.335} \quad (5)$$

where ω is expressed in 1/d, and t in years. After integration the above formula predicts different functional dependence of the rotation period on time for different turnover times, hence masses. In particular, stars with turnover times substantially longer than the Sun spin down faster and rotate slower at the same age. Fig. 8 shows the time variability of a rotation period for stars with turnover times from Table 2 and (assumed)

Table 3
Kinematic properties of stars

name	μ_α [mas]	μ_δ [mas]	V_{rad} [km/s]	U [km/s]	V [km/s]	W [km/s]	remarks
GJ 84	1317.5	-173.9	23.3	45.2	-44.5	-6.8	OD
GJ 176	659.8	-1114.7	26.0	22.6	-57.4	-14.7	OD
GJ 182	37.2	-93.9	18.2	11.3	-16.8	-9.2	YD
GJ 2036A	132.9	73.9	40.6	8.4	-35.1	-20.3	YD/OD
GJ 205	763.0	-2092.8	8.5	-22.2	-55.6	-10.2	OD
GJ 3331A	49.1	-32.7	20.0	11.5	-14.1	-9.0	YD
GJ 3367	-85.2	-77.3	-23.0	-24.4	8.0	-6.8	YD
GJ 358	-526.1	356.9	7.0	28.5	-6.7	-2.8	YD
GJ 382	-152.9	-242.9	7.6	2.4	-12.5	-2.8	YD
GJ 431	-715.8	170.8	6.0	32.8	-17.2	-1.2	YD
GJ 494	-618.8	-16.6	-11.7	29.3	-17.2	-10.3	YD
GJ 551	-3775.4	769.3	-21.6	28.9	1.5	13.7	YD
GJ 569A	276.1	-122.4	-7.2	-7.8	3.2	-13.3	YD
GJ 9520	78.4	129.4	6.5	-0.4	9.5	4.3	YD
GJ 618A	-729.3	991.2	43.0	-35.6	-3.2	54.9	OD
GJ 2123A	65.8	-109.4	-18.0	17.8	1.3	-9.0	YD
GJ 669 A	-221.2	349.0	-33.6	34.5	-19.1	-3.6	YD
GJ 674	573.4	-879.6	-10.0	14.5	-5.1	-19.3	YD
GJ 729	637.6	-192.5	-11.5	13.0	-1.2	-7.1	YD
GJ 799AB	269.3	-365.7	5.0	2.7	-15.5	-16.2	YD
GJ 803	280.4	-360.1	-4.6	10.2	-16.4	-10.4	YD
GJ 1264A	300.8	-291.1	-4.5	26.0	-19.2	-1.7	YD
GJ 867A	450.6	-79.9	-8.7	17.8	-10.3	-2.1	YD
GJ 890	101.6	-24.1	7.0	6.2	-3.1	-10.9	YD
GJ 897A	317.0	-234.0	-2.6	13.1	-24.6	-7.8	YD
GJ 411	-580.5	-4770.0	-84.7	-46.2	-53.8	-74.3	OD
GJ 699	-798.7	10337.8	-110.6	141.1	4.5	18.2	OD/H

The columns give name of a star, proper motion in right ascension and declination, radial velocity, three galactic components of velocity, kinematical class (see text)

initial rotation period of 1 d. For comparison, $P_{\text{rot}}(t)$ of a star with turnover time corresponding to the solar value (15.5 d) and to the value from plateau (25.5 d) are also given. Overplotted are the observed rotation periods of the Sun, Proxima and all six OD stars (plotted at an age of 9.9 Gyr for better visibility). The observational point at an age of 4 Gyr corresponds to a period of 17 d, calculated from the average value of $v \sin i$ of four solar type stars with $0.60 \text{ mag} < B - V < 0.69 \text{ mag}$ measured by Pace and Pasquini (2004). Two highest lying curves correspond to $\tau_c = 95 \text{ d}$ and to this turnover time minus its estimated error, *i.e.*, $\tau_c = 65 \text{ d}$. It seems that the lower value better agrees with observations of the least massive stars. The overall agreement with observational data supports the slow down model described by Eq. (5). Note that the rotation period of a star with the initial period of a fraction of a day would vary along the curve lying correspondingly lower in Fig. 8 than the curve starting at $P_{\text{init}} = 1 \text{ d}$.

Extensive observations of chromospheric emission lines and X-ray fluxes of solar type stars in many open clusters resulted in well determined age–activity relations (*e.g.*, Barry 1988, Soderblom, Duncan and Johnson 1991, Haisch and Schmitt 1996, Güdel, Guinan and Skinner 1997). However, a direct extrapolation of a relation calibrated on stars with masses $0.7\text{--}1.1 M_\odot$ to M stars with masses several times lower is not obvious *a priori* and needs to be examined. Observations of M stars of a given

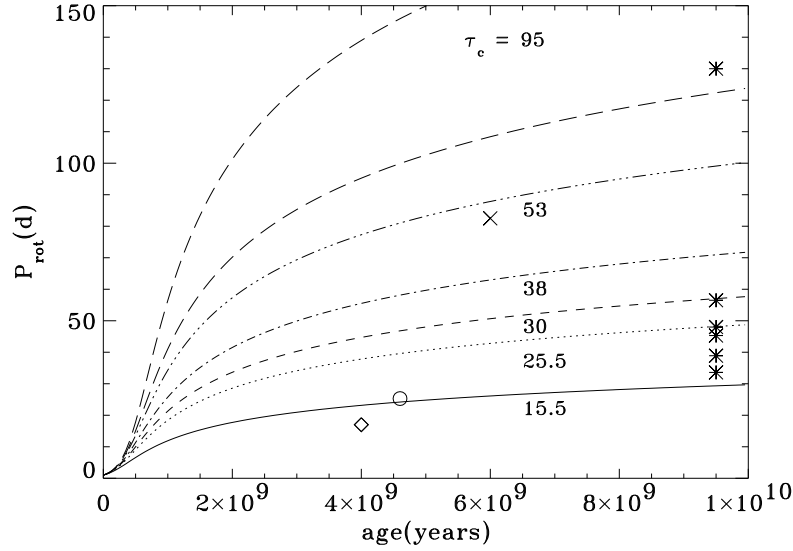


Fig. 8. Time evolution of stellar rotation period, resulting from integration of Eq. (5) with the initial value of 1 d. Different curves correspond to different turnover times, as indicated. Overclouded are observational data with the following coding: diamond – the average rotation period of four solar type members of M 67, calculated from their $v \sin i$ values, open circle – the Sun, cross – Proxima and asterisks – six old disk stars from Table 3.

age show that rotation rate and activity level increase towards later spectral subtypes (Delfosse *et al.* 1998, Scholz and Eislöffel 2005) but a mean level of activity decreases with age for a given spectral type (Hawley, Reid and Tourtellot 2000). Similarly as in case of rotation data, the activity measurements of stars with well determined ages are restricted to nearby open clusters and the observations of activity level of still older M type stars with ages of the order of 10 Gyr refer to field stars. Two such searches have recently been performed: one in H α (Silvestri, Hawley and Oswalt 2005) and the other in X-rays (Feigelson *et al.* 2004). Silvestri *et al.* (2005) observed 139 M stars in wide binaries with white dwarf companions. Ages of the binaries were determined from the cooling age of the white dwarf components. Most of the investigated M dwarfs have ages below 4 Gyr but there are also many stars with ages up to 10 Gyr (regretfully the authors do not list ages of individual stars). The results confirm earlier findings that the mean activity level increases with decreasing mass. The analysis of kinematics of the investigated stars showed that active stars (of dMe type) have lower space velocities and are confined to thin disk. Inactive stars (of dM type) have systematically higher space velocities, characteristic of thick disk. Feigelson *et al.* (2004) analyzed the results of a deep, pencil-beam X-ray observations in a Galactic high-latitude field, obtained with Chandra. The observations of late-type MS stars are compared with predictions based on convolution of X-ray luminosity function with the known spatial distribution of old disk stars. The authors came to the conclusion that stellar X-ray luminosities decrease with age like $L_x \propto t^{-2}$ over $1 < t < 11$ Gyr, rather than $L_x \propto t^{-1}$ resulting from simple power laws: $v_{\text{rot}} \propto t^{-1/2}$ (Skumanich 1972) and $L_x \propto v_{\text{rot}}^2$ (Pallavicini *et al.* 1981, Pizzolato *et al.* 2003). The result shows that at least one the above power laws does not apply to M stars which dominate stellar source counts in the search by Feigelson *et al.* (2004).

Stępień (1988, 1994) suggested an alternative period-activity relation, in which the activity level depends exponentially on the Rossby number.

We have shown in the previous section that the X-ray activity of M stars decreases

with the Rossby number similarly to that of G–K type stars *i.e.*,

$$\log R_x \propto -(1.45 \pm 0.12) Ro. \quad (6)$$

Quality of fit of both, power and exponential relations to observational data is similar (Hempelmann *et al.* 1995) so it is not possible to discriminate between them on the basis of the rotation-activity diagram alone. However, the age–activity relation resulting from Eq. (6), together with Eq. (4), is in a much better agreement with the results obtained by Feigelson *et al.* (2004) than the power relation $L_x \propto t^{-1}$.

Using turnover times given in Table 2, Rossby numbers of six old disk stars were calculated and the average value obtained: $\overline{Ro} = 1.2 \pm 0.4$. The uncertainty of this value comes from errors of turnover times and the scatter of individual Rossby numbers. Assuming that the obtained value of \overline{Ro} is typical for old M type stars and that young M type stars have $Ro \ll 1$, we obtain:

$$(\log R_x)_{\text{young}} - (\log R_x)_{\text{old}} = 1.7 \pm 0.50. \quad (7)$$

X-ray observations of Hyades (Reid *et al.* 1995) and Praesepe (Franciosini *et al.* 2003), open clusters with ages about 600 Myr and 800 Myr respectively, show their M stars still in saturation regime. Assuming the age of M stars at the end of saturation regime ≈ 1 Gyr and of old stars ≈ 10 Gyr, the 10-fold increase in age should result, according to Eq. (7), in a decrease of X-ray flux by a factor $10^{-1.7}$. This prediction can directly be compared with observations. All six OD stars were observed in X-rays (see Table 1) and their average value of $\log R_x$ is equal to -4.84 . The average value of $\log R_x$ of young, rapidly rotating stars is about $-(3.0-3.2)$ (Pizzolato *et al.* 2003, see also Fig. 5), so the observed difference $(\log R_x)_{\text{young}} - (\log R_x)_{\text{old}} \approx 1.6-1.8$ is in excellent agreement with the predictions based on Eq. (7) and in a fair agreement with the results by Feigelson *et al.* (2004).

Based on the results of the present paper we can explain why M type stars show higher activity level even if they are older and rotate much slower than more massive stars. As it was shown, the main parameter controlling activity is the Rossby number, not rotation period. The results of the present paper show that the empirical turnover time increases with decreasing mass, at least for early M types. Rotation periods of the old disk M type stars are not much longer than their turnover times so the resulting Rossby numbers are of the order of unity. Such stars should be considerably more active than massive stars with the same rotation periods but shorter turnover times. Our analysis applies to early M type stars up to about M4, with masses above the full convection limit. There is indication that empirical turnover time increases further for stars with masses as low as $0.17 M_\odot$ but a significantly more numerous sample is needed to draw meaningful conclusions.

4 Conclusions

We checked 180 nearby X-ray active M type stars for periodic light variations. Analysis of 6 seasons of ASAS photometric observations led to the detection of periodic variations in 31 objects with typical half-amplitude of 10 mmag and periods between a fraction of a day and 83 d. We interpret these variations as resulting from rotational modulation of non-uniformly spotted stellar surface. Prior to our search only three M type stars with long (at least a few tens of days) rotation periods were known. We detected 9 more stars with rotation periods longer than 10 d which is the approximate limiting period of saturation for early M dwarf stars. Our data show that also M type stars obey period-activity relation such that activity decreases with increasing period.

The relation is mass dependent, similarly as in G and K type stars. To obtain a single period-activity relation rotation for all stars, their periods should be scaled down by mass dependent factors (turnover times). The analyzed stars were divided into four mass intervals and turnover times were determined for three of them. The fourth bin, containing the least massive stars has too few data points to obtain its reliable value but a continuous increase of the turnover time with decreasing mass, down to masses of $0.1\text{--}0.2\text{ M}_{\odot}$, is suggested. We demonstrated that the formula for spin down rate of single stars, derived by Stepień (1988) also correctly predicts the evolution of rotation period of M type stars when newly determined turnover times are used. The analysis of space motions showed that all OD stars have long rotation periods with a median value of 47 days. This clearly demonstrates that M type stars spin down as they age. Assuming 10 Gyr for the age of OD stars we showed that the exponential period-activity relation, together with the spin down rate formula, correctly predicts the decrease of X-ray activity with age, as observed by Feigelson *et al.* (2004). The observations of Feigelson *et al.* are at odds with an age-activity power relation resulting from the Skumanich law and period-activity relation suggested by Pallavicini *et al.* (1981) and Pizzolato *et al.* (2003).

It would be desirable to extend the period search to late M stars but to this purpose photometric observations reaching fainter stars than present day ASAS are needed.

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